AD-A224 707

SECURITY CLASSIFICATION OF THIS PAGE

DTIC FILE COPY

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

2

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE N/A	
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S) AFOSR-TR- 90 0807
6a. NAME OF PERFORMING ORGANIZATION University of Maryland 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION AFOSR
6c. ADDRESS (City, State, and ZIP Code) College Park, MD 20742	7b. ADDRESS (City, State, and ZIP Code) Bldg. 410 Bolling AFB, Washington, D.C. 20332-6448
8a. NAME OF FUNDING/SPONSORING ORGANIZATION AFOSR 8b. OFFICE SYMBOL (If applicable) NM	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER AFOSR-87-0073
8c. ADDRESS (City, State, and ZIP Code) Bldg. 410 Bolling AFB, Washington, D.C. 20332-6448	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO: 61103D PROJECT NO: 3484 TASK NO: AS WORK UNIT ACCESSION NO:

11. TITLE (Include Security Classification)
Control of Complex Multibody Spacecraft

12. PERSONAL AUTHOR(S)
Professor P.S. Krishnaprasad

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Final	FROM 12-1-88 TO 12-31-89		13

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

The Project C-MULTICS (Control of Complex Multibody Spacecraft) is a center of excellence at the University of Maryland. The work supported by this project is concerned with the modeling, analysis, control and simulation of large scale complex multibody spacecraft with rigid and flexible components.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL Dr. Arje Nachman	22b. TELEPHONE (Include Area Code) (202) 767-4939 22c. OFFICE SYMBOL NM

DD Form 1473, JUN 86 Previous editions are obsolete. SECURITY CLASSIFICATION OF THIS PAGE

SYSTEMS RESEARCH CENTER

University of Maryland

College Park, MD 20742

Annual Technical Report
December 1, 1988 - December 31, 1989

Control of Complex Multibody Spacecraft

AFOSR - URI Grant No. AFOSR-87-0073

Principal Investigator:

Professor P.S. Krishnaprasad
Department of Electrical Engineering
& Systems Research Center
University of Maryland
College Park, MD 20742

Co-principal Investigators:

Drs. Eyad Abed, Stuart Antman, John Baras, Carlos Berenstein, John Maddocks, Jerrold Marsden, Juan Simo.

1. Introduction

The original proposal submitted to AFOSR in April 1986 proposed a three year program of research in the control of complex multibody spacecraft. The project was renewed annually since the first 1 year award.

Section 2 below highlights the accomplishments of the project and discusses how the work of the various investigators is tied together. In particular, it also brings into focus how the initial plans of the **C-MULTICS** project have come to fruition in various areas.

The specific accomplishments of the C-MULTICS project are to be found in the publications of the project personnel (faculty and students). The following is a list of key papers acknowledging the support of the AFOSR-URI Award.

1. E.H. Abed, and S.P. Boyd (1988), "Perturbation Bounds for Prescribed Robust Stability," *Proc. 27th IEEE Conf. Dec. Control*, Austin, December 1988.
2. E.H. Abed, and J.-H. Fu (1988), "Lyapunov Functions for Critical Nonlinear Systems," *Proc. 27th IEEE Conf. Dec. Control*, Austin, December 1988.
3. E.H. Abed, and D.-C. Liaw (1988), "On the Stabilization of Tethered Satellite Systems," *Proc. Second Conf. on Nonlinear Vibrations, Stability and Dynamics of Structures and Mechanics*, VPI, Blacksburg, June 1-3, 1988.
4. S.S. Antman (1988), "The Paradoxical Asymptotic Status of Massless Springs," *SIAM Journal of Applied Mathematics*, 48, 1319–1334.
5. S.S. Antman (1988), "Asymptotic Analysis of Quasilinear Parabolic Equations Describing the Motion of Viscoelastic Bars," in preparation.
6. S.S. Antman, and P. Negro'n-Marrero (1988), "Singular Global Buckling Problems for Anisotropic Plates," *Technical Report*, Univ. of Maryland.
7. J.S. Baras, W.H. Bennett, and G.H. Kwatny (1987), "Robustness Issues in Boundary Feedback of Flexible Structures," *Proc. American Control Conf.*, invited paper, 1301–1313.

8. J.S. Baras, A Bensoussan, and M.R. James (1988), "Dynamic Observers as Asymptotic Limits of Recursive Filters: Special Cases," *SIAM Journal of Applied Mathematics*, Vol. 48, No. 5, October 1988.

9. J.S. Baras, and M.R. James (1988), "Design of Observers," *Proc. INRIA Conf. Anal. Opt. Systems*, June 1988.

10. C.A. Berenstein (1987), "On an Overdetermined Neumann Problem," *Seminari Di Geometria*, 1986, 21-26, also *Technical Report SRC-TR-87-95*, Systems Research Center, Univ. of Maryland.

11. C.A. Berenstein, R. Gay, and A. Yger (1989), "Analytic Continuation of Currents and Division Problems," *Forum Math.*, Vol. 1, 1989, pp. 15-51.

12. C.A. Berenstein, and D.C. Struppa (1986) "Small Degree Solutions for the Polynomial Bezout Equations," *Technical Report SRC-TR-86-74*, Systems Research Center, Univ. of Maryland.

13. C.A. Berenstein, and A. Yger (1989), "Analytic Bezout Identities," *Advances in Applied Mathematics*, Vol. 10, 1989, pp. 51-74.

14. C.A. Berenstein, and A. Yger (1989), "Effective Bezout Identities in $Q[z_1, \cdots, z_n]$," preprint.

15. M.R. James, and J.S. Baras (1988), "Nonlinear Filtering and Large Deviations: A PDE-Control Theoretic Approach," *Stochastics*, Vol. 23, 391-412.

16. M.R. James (1988), "Nonlinear Filtering and Observers," *Ph.D. dissertation*, Dept. of Mathematics, University of Maryland, College Park.

17. R. Grossman, P.S. Krishnaprasad and J.E. Marsden (1987) "The Dynamics of Two Coupled Three Dimensional Rigid Bodies" in F. Salam & M. Levi, eds. ***Dynamical Systems Approaches to Nonlinear Problems in Systems and Circuits,*** pp. 373-378, SIAM Publ., Philadelphia, 1988.

18. P.S. Krishnaprasad (1989) "Eulerian Many-Body Problems" to appear in ***Contemp. Math.***, AMS. (SRC TR-89-15)

19. D.-C. Liaw, and E.H. Abed (1988), "Stability Analysis and Control of Tethered Satellites," *Proc. USAF/NASA Workshop on Model Determination for Large Space Structures*, Caltech, March 22-24, 1988.

20. J.H. Maddocks (1987), "Restricted Quadratic Forms, Inertia Theorems and the Schur Complement," *Linear Algebra and Appl.*, 108, pp. 1–36.

21. Y.G. Oh, N. Sreenath, P.S. Krishnaprasad and J.E. Marsden (1988), "The Dynamics of Coupled Planar Rigid Bodies Part II: Bifurcation, Periodic Orbits, and Chaos", (in press) *J. Dynamics & Differential Equations.*

22. T. Posbergh (1988) Ph.D. Thesis, University of Maryland, *Modeling and Control of Mixed and Flexible Structures*, Also, Systems Research Center Technical Report *SRC TR88-58.*

23. T. Posbergh, P.S. Krishnaprasad and J.E. Marsden (1987), "Stability Analysis of a Rigid Body with a Flexible Attachment using the Energy-Casimir Method" in M. Luksic, C. F. Martin, W. Shadwick eds. *Differential Geometry : The Interface between Pure and Applied Mathematics*, in series, *Contemporary Math.*, Vol. 68, pp. 253-273. AMS, Providence.

24. L. Saydy, E.H. Abed, and A.L. Tits (1988), "On the Stabilization of Nonlinear Control Systems with Prescribed Regions of Asymptotic Stability," *Proc. 27th IEEE Conf. Dec. Control,* Austin, December 1988.

25. A. Sela (1988) "Client-Server Model Implementation," *Technical Report*, Systems Research Center, University of Maryland.

26. J.C. Simo, and D.D. Fox (1988), "On a Stress Resultant Geometrically Exact Shell Model. Part I: Formulation and Optimal Parametrization," to appear in *Comp. Meth. Appl. Mech. Engg.*

27. J.C. Simo, D.D. Fox, and M.S. Rifai (1988), "On a Stress Resultant Geometrically Exact Shell Model. Part II: The Linear Theory; Computational Aspects," to appear in *Comp. Meth. Appl. Mech. Engg.*

28. J.C. Simo, D.D. Fox, and M.S. Rifai (1988), "On a Stress Resultant Geometrically Exact Shell Model. Part III: Computational Aspects of the Nonlinear Theory," submitted to *Comp. Meth. Appl. Mech. Engg.*

29. J.C. Simo, D.D. Fox, and M.S. Rifai (1988), "Formulation and Computational Aspects of a Stress Resultant Geometrically Exact Shell Model," *Proceedings of International Conference on Computational Engineering Science*, Atlanta, Georgia, April 1988. Invited Paper.

30. J.C. Simo, J.E. Marsden and P.S. Krishnaprasad (1988), "The Hamiltonian Structure of Nonlinear Elasticity: The Material and Convective Representation of Rods, Plates and Shells", *Arch. Rat. Mech. & Anal.*, Vol. 104, No. 2, pp. 125-183.

31. J.C. Simo, T. Posbergh and J.E. Marsden (1988), "Nonlinear Stability of Geometrically Exact Rods by the Energy-Momentum Method". *Preprint*, Stanford University, Division of Applied Mechanics.

32. N. Sreenath (1987) Ph.D. Thesis, University of Maryland. *Modeling and Control of Multibody Systems*. Also, Systems Research Center Technical Report *SRC TR87-163*.

33. N. Sreenath, and P.S. Krishnaprasad (1988), "Multibody Simulation in an Object Oriented Programming Environment," in R. Grossman ed.*Advances in Symbolic Computing*, SIAM Publ., Philadelphia (in press).

34. N. Sreenath, Y.G. Oh, P.S. Krishnaprasad and J.E. Marsden (1988), "The Dynamics of Coupled Planar Rigid Bodies Part I: Reduction, Equilibria & Stability," *Dynamics & Stability of Systems*, Vol. 3, No. 1&2, pp. 25–49.

35. L.-S. Wang, P.S. Krishnaprasad (1989), "Relative Equilibria of Two Rigid Bodies connected by a Ball-in-Socket Joint," Submitted to the *IEEE Conference on Decision and Control*, Dec. 1989.

36. R. Yang, P.S. Krishnaprasad (1989), "On the Dynamics of Four-Bar Linkages," Submitted to the *IEEE Conference on Decision and Control*, Dec. 1989.

37. S.S. Antman (1988), "A Zero Dimensional Shock"., Quart. Appl. Math., vol 46. (in press).

Several other papers and Ph.D. dissertations (L.-S. Wang, R. Yang, D.-C. Liaw, at Maryland and G. Patrick at Berkeley) are in preparation which relate to the main themes of the C–MULTICS project.

2. Accomplishments of Project C-MULTICS

Here we highlight our main accomplishments since October 1986. We refer to the work contained in the papers listed in section 1 (we shall refer to them by numbers used there). The descriptions of accomplishments are organized into various categories along the lines of the original proposal.

2.1 Analytical Mechanics and Modeling

We made very significant progress in this area. In paper (30), the hamiltonian structures underlying the geometrically exact models of elasticity were worked out for the first time. This is based on the groundwork laid in the earlier paper of Krishnaprasad and Marsden (Arch. Rat. Mech. Anals. vol 98, no. 1, pp 71 - 93, 1987), where the authors also initiated a program for the study of stability questions for rigid bodies with flexible attachments using the energy-Casimir method. The bracket structures for rod models and plates given in (30) are relevant to the study of stability questions for relative equilibria (eg. a steadily rotating beam-like structure in orbit). The energy- Casimir program for solid mechanics has been further refined and systematized in (23) and has been applied to rod models by us and by other investigators such as Anthony Bloch of Cornell University. Tom Posbergh's Ph. D. dissertation contains a number of interesting results along these lines.

One of the more fundamental conclusions of our work in the area of stability of geometrically exact models of continuum mechanics has been the observation that in certain classes of problems *Casimir functions may not exist due to global geometric reasons.* As a consequence, a new technique *the energy-momentum method,* has been developed. This technique has been applied to rod models in (31) and appears to be very promising. The main idea here is to work entirely in the spatial representation of elasticity and impose the necessary constraints associated with symmetries and momentum maps in carrying out the second variation test. The exploitation of these ideas has been the principal program of Tom Posbergh's post-doctoral work at Stanford with Simo. There are close links between the energy-momentum approach and the constrained variation technique of Maddocks (20).

In (4), Antman has undertaken a deep study of the behavior of nonlinearly elastic and visoelastic materials. In particular, as we take the limit of mass density going to zero of a massy spring with such elastic characteristics connected to a point mass, the dynamics of the point mass displays history dependence! This paper is part of a broad program to understand the effects of damping in materials on the dynamic behavior of multibody systems. In a further study (5) by Antman generalizing the problem of (4) by replacing the massy spring by a light planar flexible rod, very different characteristics emerge. For instance, the leading term in the asymptotic expansion of longitudinal motion is given by an ordinary functional differential equation. No memory effects arise. In (37), Antman introduces a type of shock structure in nonlinear springs that can be regularized by a class of dissipative mechanisms. This work may have substantial relevance to questions about the modeling of joints in large space structures.

The papers (21), (34), and the dissertation of Sreenath (32) represent major progress in our understanding of the qualitative behavior of planar systems of coupled rigid bodies. In addition to the discovery of the underlying Hamilton-Poisson structures and related energy-Casimir analysis of the stability of various equilibrium shapes, we have begun to understand the occurence of periodic solutions and complex motions in such systems. In the Ph.D. research of George Patrick at Berkeley, the results of (17) are being used and extended to investigate the bifurcation phenomena in three dimensional coupled rigid body systems. In the Ph.D research of L-S. Wang at Maryland, questions of computation of relative equilibria and attitude control of the same class of problem is considered (35).

In the papers of Liaw and Abed (19), (3), the question of stability of Hopf bifurcations arising in tethered satellite systems is addressed. The authors also use the earlier work of Fu and Abed to investigate the stabilization problem.

2.2 Nonlinear & Distributed Control

Our contributions in this area fall into several categories. New results on the feedback control of planar multibody systems appear in the Ph.D. dissertation (32) of N. Sreenath. It has been shown that planar multibody systems are globally controllable with all joint torques active and one external torque, say on body 1, active. Thus it is possible to inertially reorient and reconfigure such a system using joint torques and one external torque such as produced by gas jets. A related feedback stabilization theorem appealing to LaSalle's invariance principle is also proved in that work. Further investigation of time optimal control problems in multibody systems is under way. Some recent numerial studies in this connection have been made by Dr. N. Sreenath at Case Western Reserve University.

At the Intelligent Servosystems Laboratory at the University of Maryland, experiments have been under way for some time to investigate the problem of controlling a single link flexible are. The necessary test bed for this purpose was built with the support of Westinghouse Defense Electronics. In the dissertation of Posbergh (22), a very interesting distributed parameter model of the above experimental setup has been developed. He has shown that a constrained (i.e. inextensible and nonshearable) version of the planar geometrically exact rod model is most appropriate. The resulting system is an integro-partial differential equation and has led to a variety of control-theoretic questions. For example, we have been able to show that the empirically observed frequency response of the flexible arm experiment is better predicted by the geometrically exact model than by *ad hoc* linearizations popular in the literature. A natural Galerkin approximation to this infinite dimensional system can be interpreted as a chain of rigid bodies with joint compliance. This nonlinear approximation suggests a number of different nonlinear control schemes for the flexible arm experiment. *The methodology adopted here is systematic and generalizes to three dimensional rods and plates.*

In Posbergh's thesis, a rigorous study is made of various linearizations of the above infinite dimensional model. The necessary distributed parameter control theory (in state space and in frequency domain) has been developed. One of the useful results of (22) is the observation that Slemrod's saturating control law for stabilization of the linearized model is in fact applicable to the flexible arm experiment.

One of the key tasks in designing control systems for distributed parameter systems, is to work out observers. One can then attempt to mimic the finite dimensional frequency domain approach based on observer-controller schemes. The papers (8), (9), (15) and the thesis (16) of James, attack the problem of constructing observers for nonlinear and distributed parameter systems. Using techniques based on filtering theory, the authors construct state observers in a systematic manner. Extensions of the ideas of (9) to hyperbolic systems should be especially useful in the control synthesis problem for flexible structures.

In (10) - (14), Berenstein considers the fundamental problem of solving Bezout equations which appears in the design of feedback controllers for linear systems. New results are given to reduce the degrees of the solutions. This is turn will reduce the degrees of the feedback compensators.

In the papers of Abed and coworkers (1)-(3), a number of key questions of interest in the design of controllers for multibody systems are addressed. The hamiltonian nature of multibody systems leads to critical cases in stability. Methods based on bifurcation analysis are adopted in some of this work. New Lyapunov analyses for prescribed domains of attraction are given.

2.3 Advanced Computation Research

We have made significant progress in developing new software tools to model, and numerically simulate multibody systems with rigid and flexible components. We have also developed new software tools to design controllers for such systems.

At Stanford University, under the leadership of Juan Simo, nonlinear finite element code based on geometrically exact models has been developed to run on a Convex minisupercomputer. The code has been tested on a variety of problems including the spin-up of a flexible helicopter blade. This latter simulation has shown the striking deviations that appear when *ad hoc* linearizations are used instead of geometrically exact models. Posbergh is working on ways to adapt this code to the nonshearable, inextensible rod model of the flexible arm experiment at Maryland. In addition, we note the major advances in numerical integration of geometrically exact shell models in the work of Juan Simo and his collaborators Fox and Rifai (see (26)-(29)). Some of the code developed at Stanford for finite element models and at Maryland for coupled rigid body models has the added feature of conserving certain invariants of the underlying dynamics.

At the University of Maryland we have had access to two Symbolics 3600 series Lisp machines. This has made it possible for us to develop sophisticated symbolic algebraic systems in a Zetalisp environment to do *automatic model generation, code generation and animation* for multibody systems. A system known as OOPSS (Object Oriented Planar Systems Simulator) was written by N. Sreenath (33). This system has proved to be a useful tool in exploring the equilibria, stability and asymptotic feedback stabilization of planar systems.

We have also acquired through URI funding a Silicon Graphics IRIS 3130 graphics workstation to study three dimensional animation problems for multibody systems. Generic tools based on Interprocess Communication have been created to drive (over Ethernet) the animations on the IRIS from simulation programs residing in other workstations such as a Sun 3/260. One of our aims has been to focus on methods that can be adapted to future multiprocessing extensions of our laboratory's computing resources. The current status of our implementation together with examples is discussed in (25). We thus have the computation tools needed to study three dimensional multibody dynamics including flexible components.

L-S. Wang, a graduate student supported under the URI project, is one of the originators (with Fan, Tits and Konninckx) of a package known as CONSOLE. This package supports the optimization-based design of control systems from rational engineering specifications. It has extensive graphics to identify design tradeoffs and is highly interactive.

The system has been used with success in designing feedback gains for the real-time control of the Maryland flexible arm experiment.

In collaboration with one of our visitors (Professor Akinori Yonezawa from Japan), we have made progress in the development of parallel Newton-Euler algorithms for multibody systems. This work is continuing with one graduate student. Our algorithms appear to be quite new and are well-suited for concurrent object oriented implementation.

2.4 Laboratory Development

The past two and a half years have been a period of steady growth for the *Intelligent Servosystems Laboratory.* The laboratory has now two Silicon Graphics workstations, an IRIS 2400 obtained through Systems Research Center Funds and upgraded through URI funds to a Turbo level and additional bit planes,and an IRIS 3130 obtained through URI funds. Also, we have a SUN 3/260 and a SUN 3/160S file server partially funded by the URI grant, a SUN 3/50, and a Texas Instruments Explorer Lisp machine. The machines in the laboratory are networked via a local Ethernet and are connected to other machines on the Maryland campus broadband network through the SUN 3/260 gateway. The Explorer will eventually support most of the symbolic computation needs of the laboratory. Thus it will serve as the model/code generating engine while the IRIS workstations serve as fast animators. The SUN is the principal number-crunching tool. The laboratory houses a flexible arm experiment and other experiments of interest in robotics. It has also received hardware gifts from COMSAT and INTELSAT to do structural control experiments.

In the past two years, some twenty students (graduate and undergraduate) have participated in the software development and experimental work of the laboratory. Several of these students have been supported by fellowships from the Systems Research Center. The quality of the work has been high and there is evidence of some genuine synergism at work.

The Intelligent Servosystems Laboratory occupies approximately 1600 square feet of high quality space in the A.V. Williams Building of the College Park Campus.

2.5 Visitor Program and Workshops

In the course of the current project, we have had several visitors to the University of Maryland, who have interacted with the faculty and students participating in the C-MULTICS project. Typically, seminars have been given by the visitors and special discussion periods set aside. The visitors include Professor Hans Weinberger of the University of Minnesota (one semester), Professor Ruth Curtain of the University of Groningen (six weeks), and Professor Akinori Yonezawa of Tokyo Institute of Technology (ten weeks), and Professor Peter Crouch of Arizona State (one week). Professor John Baillieul of Boston University and Professor Eduardo Sontag of Rutgers University have been at Maryland to give seminars at the invitation of the URI Project. Additional visits by Professor Anthony Bloch of Cornell University, Professor Shankar Sastry of U.C. Berkeley, Dr. Debra Lewis of Cornell University, Dr. Richard Montgomery of MSRI, Berkeley, and Professor Golubitsky of the University of Houston are being planned.

A major event of direct relevance to the present project was the AMS-SIAM-IMS Summer Research Conference on *Control Theory and Multibody Systems* held under the auspices of the American Mathematical Society during the week July 30 - August 5, 1988. The conference was held in Bowdoin College, Brunswick,Maine. The organizers were P.S. Krishnaprasad, J.E. Marsden and J.C. Simo. The conference featured some thirty invited talks and nearly fifty supported participants and served as a forum for very stimulating exchange among experts in diverse fields such as multibody dynamics, hamiltonian control theory, distributed parameter control theory, bifurcation theory, geometric mechanics, and elasticity. A proceedings volume in the series on Contemporary Mathematics of the AMS (vol. 97), has been published and should serve as a useful guidepost to the recent developments.

2.6 Air Force Laboratory Interactions

We have been exchanging information with Air Force Laboratory Scientists on various technical matters of interest. During a recent visit to the Air Force Weapons Laboratory at Kirtland Air Force Base, P.S. Krishnaprasad gave a two hour presentation on the C-MULTICS project including a video tape demonstration of some of our multibody dynamics software. There were preliminary discussions on the possibility of participating in a study related to the ongoing experiments in the area of precision slewing/pointing at AFWL. The host for the visit was Mr. Dave Founds, representing Col. Ed Oliver and the research group at AFWL. It appears that there are excellent opportunities for us to contribute analytical support to the experimental work at AFWL. We hope to renew these contacts in the very near future. There has been a similar, earlier visit to the Astronautics Laboratory at Edwards Air Force Base hosted by Dr. Alok Das.